An Evaluation of the Density Management Diagram for Coastal Douglas-fir

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ABSTRACT

Yield predictions based on Drew and Flewelling's (1979) Density Management Diagram for coastal Douglas-fir, *Pseudotsuga menziesii* (Mirb.) Franco, were compared with remeasured plot data from British Columbia. The diagram overestimated standing volume by 64% and mean diameter by 24%, on average. Volumes predicted for plantations established at initial densities between 300 and 3000 trees per hectare exceeded nearly all the plots in the data base. Because of the unattainable production targets set by the diagram, strategic plans based on its predictions would be seriously in error. Consequently, the diagram cannot be used in its current form as a silvicultural planning tool in stands of Douglas-fir on the coast of British Columbia.

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INTRODUCTION

The Density Management Diagram (Drew and Flewelling 1979) is the graphical representation of a stand growth model. The simple structure of the model permits all the usual features (i.e., volume growth, diameter growth and mortality) to be displayed on one graph.

The diagram is an attractive device for silvicultural planning because it allows the user to set a production target and then select combinations of initial spacings and thinnings that will achieve the objective. Furthermore, the user can evaluate alternative treatments in the field, without a computer.

The effectiveness of the diagram as a planning tool, however, depends more on the accuracy of the underlying model than on ease of use. Inaccurate or biased predictions may have serious consequences if they rank the effectiveness of alternative treatments incorrectly. Yet none of the previous reports on the Density Management Diagram included a detailed evaluation of the model. Most describe only its derivation and application. The purpose of this paper, then, is to evaluate the yield predictions made with the Density Management Diagram for coastal Douglas-fir.

BACKGROUND

The Density Management Diagram is based on an allometric relationship first observed by Japanese scientists in pure, even-aged stands of annual plants. Tadaki and Shidei (1959) and Yoda *et al.* (1963) found that mortality from intra-specific competition (i.e., self-thinning) occurred such that the relationship between the mean weight of survivors, **w**, and the number of survivors, **N**, could be described by an equation of the following form:

$$\ln w = a - 1.5 (\ln N)$$

where a = regression coefficient, and
ln = natural logarithm

On a log-log scale this relationship forms a straight line with a slope of -1.5 or -3/2. The thinning line is the biological upper limit to stand density and the trajectory of stand development during self-thinning (Fig. 1). White (1980) and Gorham (1979) demonstrated that the slope of the thinning line is approximately -3/2 for a large number of species, although the intercept varies from species to species. The relationship is now widely known as the Self-Thinning Rule, or the Three-Halves Power Law, and is regarded by many as the most universal phenomenon in the population biology of plants (Westoby 1984; Weller 1987). Drew and Flewelling (1977) introduced the Self-Thinning Rule to the North American forestry literature and subsequently developed the Density Management Diagram (Drew and Flewelling 1979) as a means of applying the rule to silvicultural planning.

Development of the Density Management Diagram

Drew and Flewelling (1979) used permanent sample plot data and graphical techniques to locate the maximum density or thinning line described in Equation 1:

$$\ln v = 10.437 - 1.5 (\ln N) \quad (1)$$

where v = mean tree volume (m^3), and
N = density (trees/ha)

The thinning line is a key feature of the Density Management Diagram. The other components, described below, were derived by Drew and Flewelling (1979) and are not normally associated with the Self-Thinning Rule. They defined relative density, R, as the ratio of actual stand density to maximum stand density for the

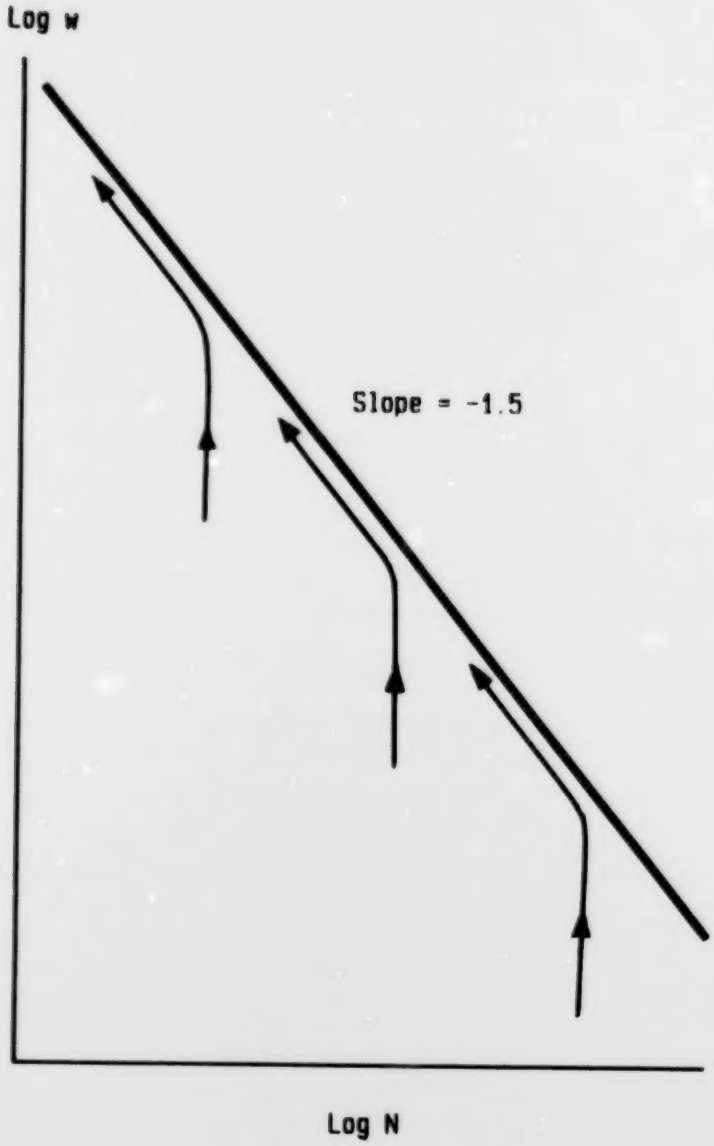

FIGURE 1. The Self-Thinning Rule or Three-Halves Power Law that relates the mean weight (w) and number (N) of survivors.

same mean volume. Next, they designated the region between 55% relative density and maximum density as the zone of imminent competition mortality (ZICM) since many plots suffered mortality well below the maximum density line. The line parallel to the thinning line at 55% relative density is the lower limit of ZICM. Another parallel line at 15% relative density denotes crown closure.

Lastly, the authors fitted two additional regressions that related the primary variables, N and v, to diameter-at-breast- height, D, and site height, H.

$$D = (30719\ v - 86.23)^{0.36716}\ (1 - 0.32375\ R^{0.44709}) \quad (2)$$

$$v = (0.0009131 + 0.00001045\ D^{2.1987})\ H^{1.10319} \quad (3)$$

The three preceding equations generate the Density Management Diagram[1] (Fig. 2).

Application

In the most common application, a silviculturist would first choose a target DBH and then use the Density Management Diagram to identify the appropriate silvicultural prescription. Drew and Flewelling (1979) recommended that stands should be grown in the region below the ZICM until the final harvest, thereby avoiding mortality related to competition. Consequently, the full production target (final harvest) is usually set at the point on the diagram where the desired DBH coincides with the lower limit of the ZICM. The user can then estimate the timing of the harvest and the volume to be harvested.

A typical application is illustrated in the following example. Suppose that a silviculturist wanted to produce stands with a mean diameter of 40 cm. The diagram predicts that a stand at the lower limit of ZICM with a 40-cm mean diameter will have attained 31.9 m in site height and can carry 416 trees per hectare with a mean volume of 1.64 m^3. The last two figures can be multiplied to give 682 m^3/ha as an estimate of total volume. According to Bruce's (1981) site curves for coastal Douglas-fir, stands will reach a height of 31.9 m at rotation age 37 if planted on site 45 m, or age 89 on site 25 m. The silviculturist would likely plant about 416 trees per hectare, or thin existing stands to that density in one or more steps, and expect to harvest a 40-cm stand with 682 m^3/ha at rotation age.

EVALUATION

The evaluation has three parts. The first section examines the characteristics of the individual points on the Density Management Diagram; the second section focuses on the dynamic elements, or how stands move from point to point on the diagram; the third section compares the diagram's predictions with data from initial spacing experiments and other remeasured plots.

The data used in this evaluation consisted of 888 measurements from 238 permanent sample plots established in pure, even-aged stands of Douglas-fir. Most of the plots are located on Vancouver Island. No fertilized plots were included. The data set is not necessarily representative of Douglas-fir on the coast because the plots were not located randomly. Nevertheless, the data do cover a wide range of conditions (Table 1).

Relationship Between Principal Variables

The choice of a production target is based on more than mean diameter alone. The corresponding length of the rotation, and the number of trees that will be harvested are also important considerations. Equations 2 and 3 together describe a static relationship between the four principal variables on the Density Management Diagram. The feasibility of the production targets on the diagram depends on the accuracy of this relationship.

[1] The original article (Drew and Flewelling 1979) contains a misprint in the diameter equation: density (N) was incorrectly substituted for relative density (R). Equation 2, above, correctly generates the Density Management Diagram.

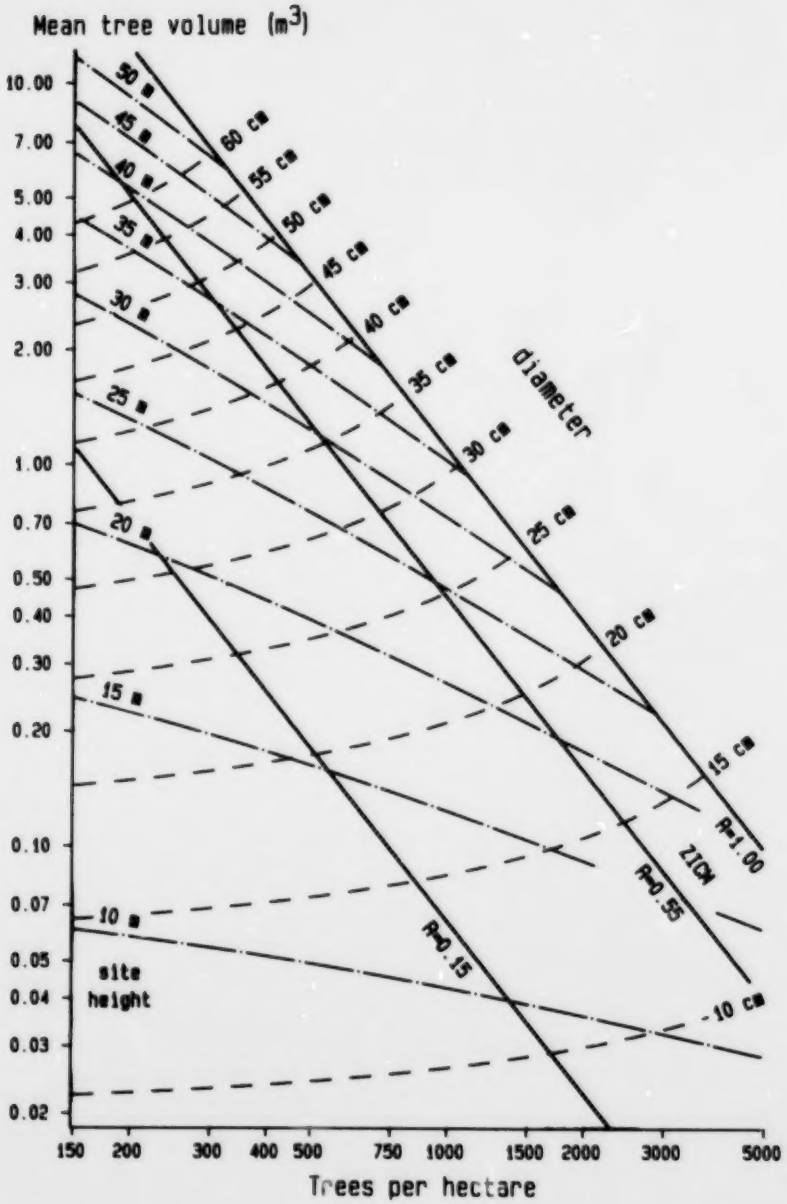

FIGURE 2. The Density Management Diagram for coastal Douglas-fir (after Drew and Flewelling [1979]).

Each point on the Density Management Diagram is a unique combination of site height, mean volume, number of trees, and diameter. Any two of the variables, however, are sufficient to describe a particular point. Therefore, two variables may be regarded as predictor variables and the remaining two can be calculated from Equations 2 and 3. Since site height and number of trees are the only two variables that can be estimated externally — from site index curves and self-thinning theory, respectively — they are used as predictor variables in the evaluation.

TABLE 1. Summary of permanent plot measurements used in the evaluation

Variable	Minimum	Mean	Maximum
Total age (years)	10	55	120
Site height (m)	3.5	26	52.5
Total volume (m^3/ha)	1	360	1400
Mean diameter (cm)	4	24	72
Number of trees (/ha)	110	1000	8660

The following analysis measures the joint effect of Equations 2 and 3 rather than evaluating each separately. An iterative routine was used to predict v and D from observed values of H and N in the data set. Total volume, V, was then calculated from v and N. Residuals (observed minus predicted) for total volume and mean diameter were calculated and plotted against site height (Fig. 3a-b).

The residual plots show that the equations tend to over-predict both volume and diameter for stands taller than 20 m (i.e., negative residuals). In general, the equations overestimate volume by 64% and mean diameter by 24% (see Table 2).

TABLE 2. Percentage over-prediction of total volume and mean diameter in Equations 2 and 3

Height class (m)	Volume (%)	Diameter (%)
3	400	79
6	127	32
9	46	4
12	26	5
15	3	0
18	29	10
21	56	21
24	60	21
27	68	22
30	68	21
33	70	19
36	83	21
39	81	19
42	63	11
45	85	18
48	78	15
51	89	17

Percentage errors exceed 100% for some plots. For example, the diagram makes poor predictions (Table 3) for the Schenstrom thinning trial at Lake Cowichan, B.C. (Warrack 1979). The comparison is particularly interesting because this experiment is the oldest Douglas-fir thinning trial in the Pacific Northwest.

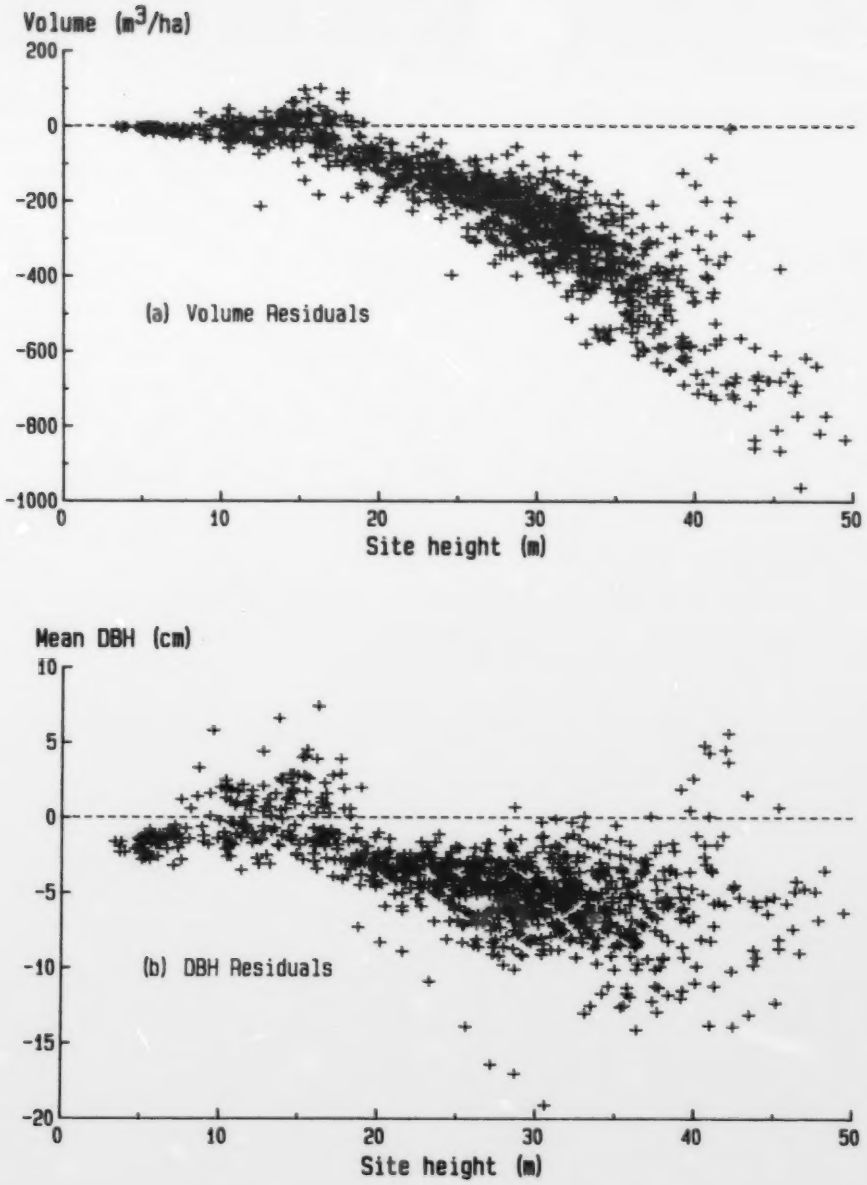

FIGURE 3. Residual values (observed minus predicted) for predictions of (a) total volume, and (b) mean diameter.

The practical implications of the bias in equations 2 and 3 can be demonstrated with the previous example in which a silviculturist wanted to grow a stand with a 40-cm mean diameter. Suppose the silviculturist, following the diagram, established a plantation with an initial density of 416 trees per hectare, and then waited until the site height reached 31.9 m. According to Table 2, the diagram overestimates mean diameter by 19%, suggesting that the average diameter would actually be about 33.6 cm. Because volume is overestimated by 70%, the predicted volume of 682 m^3/ha should be scaled down to about 400 m^3/ha.

TABLE 3. Comparison of Density Management Diagram (DMD) projections with data from the Schenstrom thinning plots at age 75

Type of Thinning	H (m)	N (/ha)	Volume (m^3/ha)			Diameter (cm)		
			Actual	DMD	Error	Actual	DMD	Error
Unthinned	44.3	778	1045	597*	53%	34.5	37.5	9%
Crown								
Heavy	45.4	205	722	1443	100%	54.5	65.5	20%
Light	46.7	255	770	1595	107%	48.5	61.2	26%
Low								
Heavy	43.0	219	534	1277	139%	46.3	61.8	33%
Light	42.2	328	652	1304	100%	41.7	52.3	25%

* The intersection of height (44.3m) and density (778 trees), which lies above the maximum density line in Figure 3, predicts volumes of 2.05 m^3 and 1597 m^3 for the average tree and stand, respectively.

The preceding example can be viewed from the perspective of the extra time the silviculturist would have to wait to make up the difference of 682 m^3/ha or 6.4 cm of diameter. An estimate of the rate of volume and diameter growth is needed to address this question. Managed stand yield tables published by the B.C. Forest Service (Mitchell and Cameron 1985) suggest that the stand would have to grow 6 m in site height to make up the 6.4-cm difference in diameter, and 8 m in site height to make up the difference in volume. Site index curves (Bruce 1981) show how long it will take a 32-m tall stand to grow an additional 6 or 8 m (see Table 4).

TABLE 4. Estimates of the additional time required on three sites for a 32-m tall stand to grow 6 or 8 m

Variable	Height growth (m)	Additional years		
		Site 25	Site 35	Site 45
Diameter	6	43	14	8
Volume	8	64	19	11

Another way to demonstrate the disagreement between principal variables is to locate an existing stand on the diagram. The unthinned plot (EP 283) in the Schenstrom thinning trial (see Table 3) can be located on the diagram by any two of the four principal variables, as noted earlier. The six possible combinations of two variables define six different points on the diagram. The relative density, R, of the six points displayed in Table 5 varies considerably. Note that three points are well above the maximum density line (R = 1.00) where, supposedly, no stands exist.

TABLE 5. Relative density of EP 283 calculated from the six possible combinations of principal variables (H, N, D, and v)

Point	Principal variables	Relative density
1	H,N	1.20
2	v,N	0.90
3	D,N	0.92
4	H,D	1.29
5	v,D	0.87
6	H,v	1.42

A serious consequence of the large percentage errors in Table 2 lies in the underestimation of the time required to reach a prescribed target, and in the selection of unrealistic objectives. In most circumstances a delay of 15 or more years would be unacceptable. A silviculturist who was aware of the true time requirement would probably choose a different target.

Stand Dynamics

Stand dynamics are appended to the Density Management Diagram, using Drew and Flewelling's (1979) interpretation of the Self-Thinning Rule. Mortality from intra-specific competition is assumed to be negligible until stands enter the zone of imminent competition mortality. Once stands cross into the ZICM, the diagram offers little guidance on the future course of stand development. Clearly stands are not expected to grow beyond the maximum density line or fall below the lower limit of ZICM. Its upper and lower limits therefore bracket all potential alternatives, as indicated by the following example.

Conventional volume-height and diameter-height curves can be derived from the Density Management Diagram. Consider the development of a plantation with 750 well-established seedlings per hectare. At 15 m of site height the diagram predicts the 750 trees will have an average volume of 0.14 m^3 and a mean diameter of 18 cm (see Fig. 4, point A). Total volume is 104 m^3/ha. The stand statistics for 25 m of site height (point B) can be predicted in the same manner (Table 6). When site height reaches 26.7 m, the stand enters the ZICM. If the stand follows the lower limit of ZICM, then at 35 m (point C), there will be only 300 surviving trees with mean volume of 2.68 m^3, total volume of 804 m^3/ha, and mean diameter of 48.0 cm. Alternatively, if the stand is not expected to suffer any competitive mortality until it reaches the maximum density line, the stand at 35 m would have 750 trees with an average volume of 1.28 m^3, total volume of 967 m^3/ha, and mean diameter of 34 cm (point D).

TABLE 6. Stand statistics corresponding to labels A,B, C, and D in Figure 4

Label	H (m)	N (/ha)	D (cm)	v (m^3)	V (m^3/ha)
A	15	750	18.0	0.14	104.0
B	25	750	27.6	0.57	427.3
C	35	300	48.0	2.68	803.0
D	35	750	34.0	1.28	967.0

This simple example shows that stands that self-thin along the maximum density line will have maximum volume, minimum mortality, and minimum diameter. Stands that self-thin along the lower limit of ZICM will have minimum volume, maximum mortality, and maximum diameter. All other patterns of mortality would presumably lie somewhere between these two extremes.

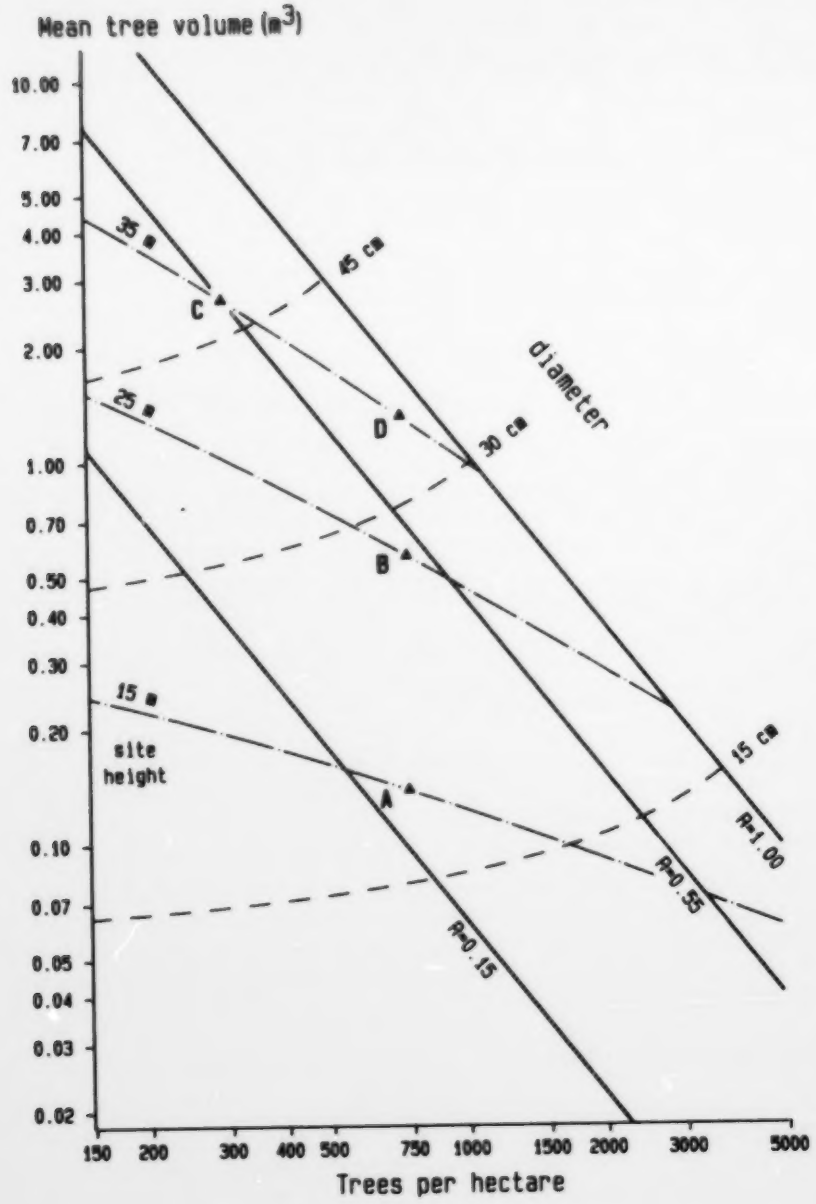

FIGURE 4. Graphical demonstration of the method for deriving volume-height relationships from the Density Management Diagram.

Following the above procedure, the Density Management Diagram was used to simulate the growth of stands planted at five different densities (Table 7). Simulated stands were assumed to self-thin along the lower limit of ZICM. The first four regimes correspond to densities found in spacing trials maintained by the Research Branch of the B.C. Forest Service. The last regime, 300 trees per hectare, is beyond the range of the data and is included to illustrate an extreme case. Volume-height and diameter-height curves for the five spacings are shown in Figures 5a and 5b, respectively.

TABLE 7. Description of initial spacing regimes used in the evaluation

Spacing		Actual density		Nominal density
(ft)	(m)	(/acre)	(/ha)	(/ha)
6	1.8	1210	2990	3000
9	2.7	538	1329	1350
12	3.7	303	747	750
15	4.6	194	478	500
19	5.8	121	300	300

The ranking of the volume-height curves agrees with the general pattern observed in spacing experiments in even-aged stands; that is, within certain limits higher initial densities produce more total volumes (Clutter *et al.* 1983). The convergence and eventual merger of the volume curves is supported by the "Law of Constant Final Yield" (Kira *et al.* 1953). For Douglas-fir, the actual rate of convergence, or the location of the point where the curves come together, must be confirmed by initial spacing trials.

The ranking of the diameter curves, with the largest diameters appearing at the widest spacings, also follows the expected pattern (Clutter *et al.* 1983). However, the merging of the diameter-height curves is unexpected and is not corroborated by spacing trials. A closer look at the mechanics of the Density Management Diagram shows that the convergence of the diameter- height curves is an artifact. According to the Self-Thinning Rule, all stands will eventually self-thin along a single thinning line, irrespective of initial density. Therefore, all initial spacing regimes will eventually converge to the same density. Since each point on the diagram is a unique combination of the principal variables (as shown earlier), all initial spacing regimes simulated with the Density Management Diagram will converge to the same volume and diameter.

This brings to light a major limitation of the Density Management Diagram: there is no consideration of the past history of the stand. For example, a 35-m tall stand with 300 trees per hectare is expected to have a mean diameter of 48 cm no matter which sequence of events leads to the current density of 300 trees per hectare. According to the diagram, initial differences in stocking density or differences in thinning history will have no effect on average stand diameter at rotation age.

Comparison with remeasurement data

Volume-height (Fig. 6a-d) and diameter-height (Fig. 7a-d) projections from the Density Management Diagram were compared with the corresponding data from Douglas-fir spacing trials. The diagram's predictions generally agree with the data, with some minor discrepancies. Volumes and diameters predicted for 3000 trees per hectare are both higher than most of the data. Diameters predicted for the widest spacings (500 and 750 trees per hectare) appear to be lower than the bulk of the data. Unfortunately there are no data for stands taller than about 25 m, where the bias in Equations 2 and 3 becomes pronounced.

The volume-height curves for 3000 and 300 trees per hectare were overlaid with the data from all the plots, including the young spacing trials. The curves in Figure 8a are based on the assumption that stands will self-thin along the lower limit of the ZICM (R = 0.55). Note that the curves merge at 36 m of site height, and beyond that point there is only one curve for all initial densities between 300 and 3000 trees per hectare. The volumes predicted at the lower limit of the ZICM exceed the mean of research plots by at least 40% at rotation (35- to 45-m site height). Only four measurements have volumes greater than the prediction.

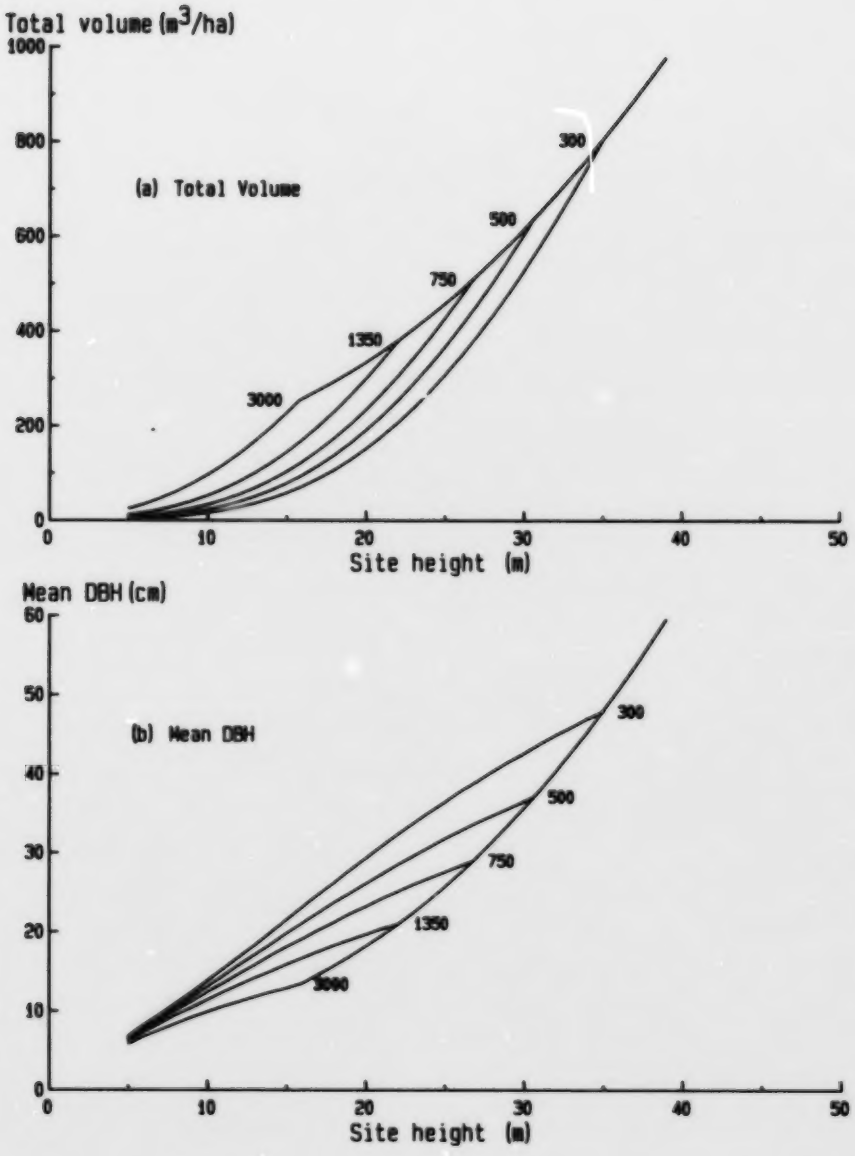

FIGURE 5. Predictions from the Density Management Diagram for (a) total volume, and (b) mean diameter in relation to site height and initial density.

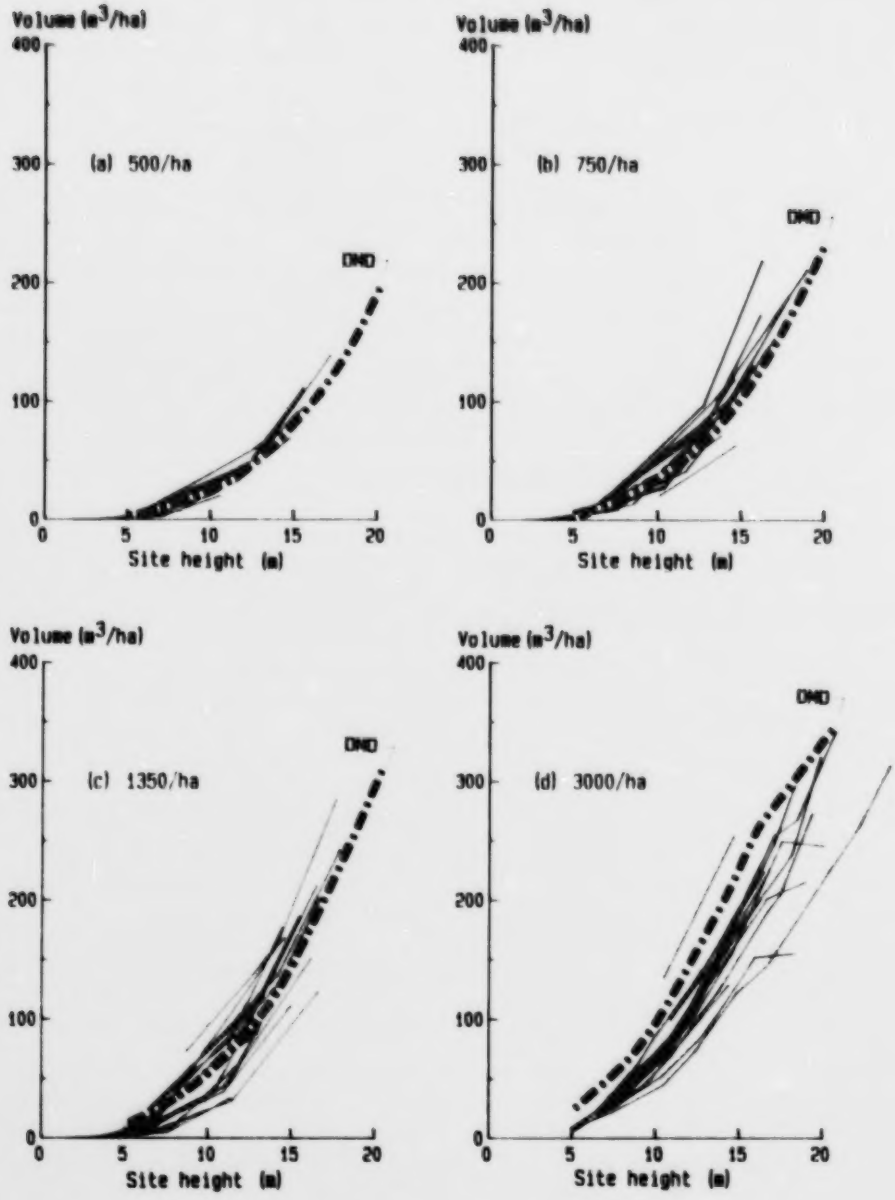

FIGURE 6. Comparison of volume-height relationships from spacing trials with initial densities of (a) 500, (b) 750, (c) 1350, and (d) 3000 trees/ha. The corresponding predictions from the Density Management Diagram (DMD) are superimposed.

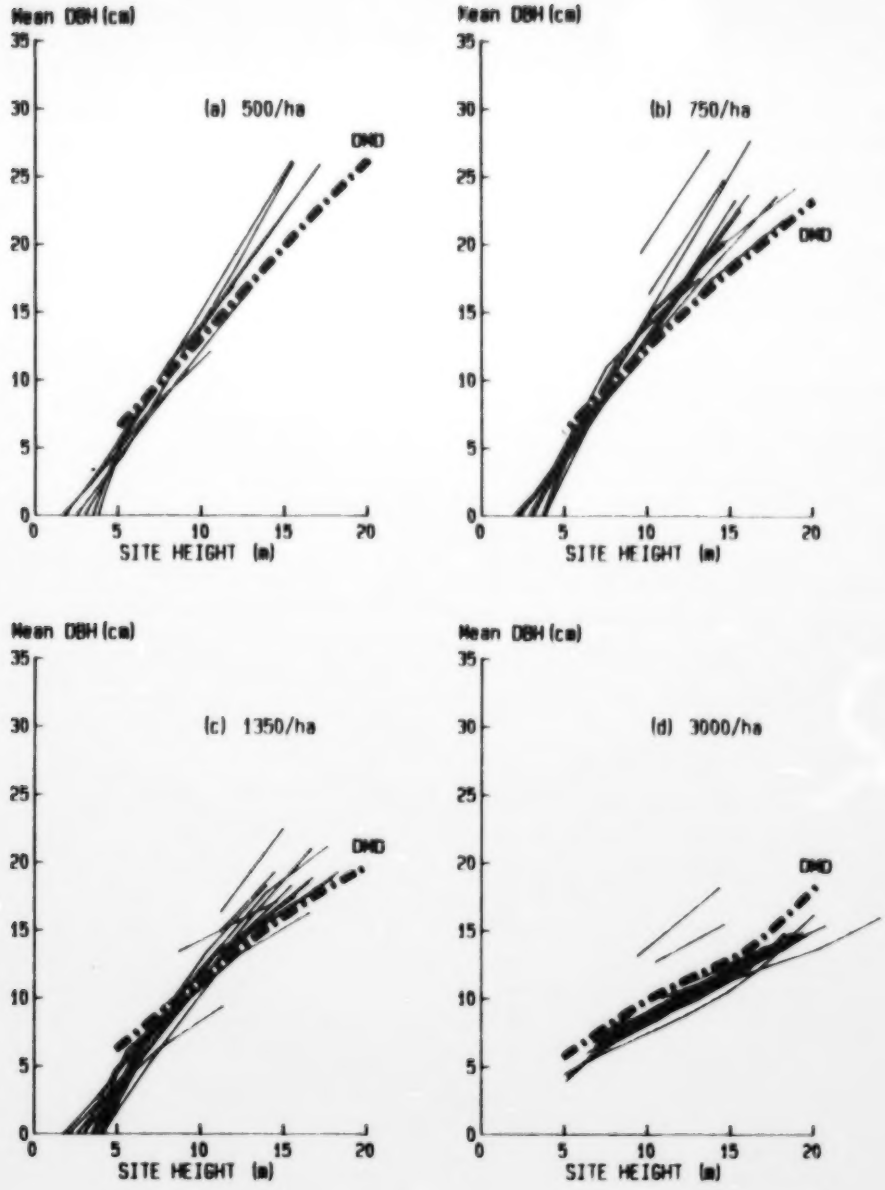

FIGURE 7. Comparison of diameter-height relationships from spacing trials with initial densities of (a) 500, (b) 750, (c) 1350, and (d) 3000 trees/ha. The corresponding predictions from the Density Management Diagram (DMD) are superimposed.

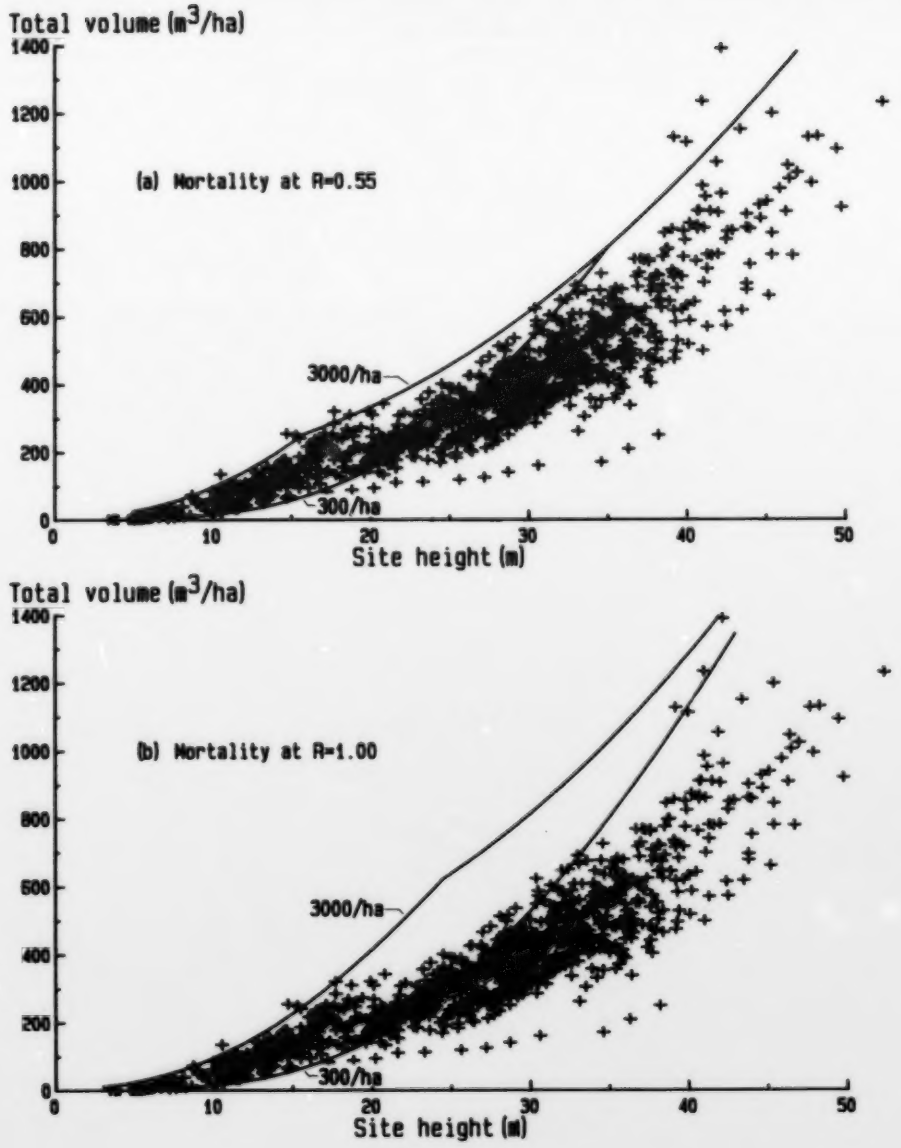

FIGURE 8. Comparison of volume-height data with values predicted by the Density Management Diagram for initial densities of 300 and 3000 trees per hectare. Stands are assumed to self-thin along (a) the lower limit of ZICM (R = 0.55) or (b) the maximum density line (R = 1.00).

The assumption that stands will self-thin along the lower limit of the ZICM, however, is not supported by the data. An analysis of relative density (R) shows that 20% of the plot measurements have values of R above 0.55. Assuming that stands will begin self-thinning at some higher relative density only increases the prediction error. Figure 8b relates the research plots to the volumes predicted for stands that self-thin along the maximum density line (R = 1.00). The predicted yield at rotation exceeds the average plot volume by 500 m^3/ha or 75%.

Some additional background information will help place these observations in perspective. The volumes of the most productive research plots (Fig. 8) are probably the best that can be expected from the plantations established today. The early research plots were located in normal stands (i.e., fully stocked), such as those depicted in normal yield tables (e.g., McArdle *et al.* 1961). The locations were carefully selected to avoid the rock outcrops, pockets of root rot, and other factors that could reduce yields below "normal" levels. Plots subsequently attacked by insects or infected by pathogens were abandoned. Volumes observed on the best research plots are certainly higher than those that an "average" managed stand can be expected to produce (Bruce 1977; Oikarinen 1978).[2] Consequently, the Density Management Diagram is likely to predict harvest volumes far in excess of what can be expected from operational plantations.

The interaction of errors in Equations 2 and 3 with errors in the dynamic component of the diagram can make predictions appear better than they really are. For example, consider predicting the yield of the unthinned control plot in Table 3. Assume that the site index curves correctly predicted the stand would be 44.3 m tall at age 75. If it were known that only 778 trees would be surviving at that age, the estimated volume would be 53% too high, as shown in Table 3. If the number of trees were not known, the user would likely follow the recommendations of Drew and Flewelling (1979) and locate a point where the height of 44.3 m coincides with lower limit of the ZICM (R = 0.55). This point occurs slightly outside of the range of Figure 3. The corresponding volume (9.8 m^3) and density (126 trees) give a predicted volume of 1236 m^3/ha at 44.3 m of site height. Compensating errors have reduced the apparent prediction error in Table 3 from 53 to 18%. The "improvement" comes from severely underestimating the number of surviving trees (126 vs 778 trees per hectare). The error in mean diameter, moreover, increased from 9 to 120%.

DISCUSSION

Many of the deficiencies of the Density Management Diagram originate with the bias in Equations 2 and 3. Other problems stem from the structure of the underlying model. To display all the pertinent features of a model in a two-dimensional diagram, Drew and Flewelling (1979) had to keep the structure of the model relatively simple. Complex and dynamic relationships found in permanent plot data could not be incorporated. In fact, all the equations could have been derived with data from temporary inventory plots. One of the simplifying assumptions is the rigid relationship between the four main variables. With this structure imposed, the model cannot account for the influence of past treatments on current stand conditions and future growth.

The issues of a simple model and a simple display should be separated. It is possible to display in two dimensions any four variables from the output of more sophisticated models. It may not be possible, however, to depict more than a few silvicultural alternatives on the same diagram. Using computer models to examine production targets and evaluate treatment options can be a complicated process, yet the decisions to be made are so important that it is undoubtedly worth the extra effort.

The primary function of a device like the Density Management Diagram is to help a silviculturist select an appropriate silvicultural prescription from among several alternatives. While no decision aid can claim to lead to the correct decision every time, a device that so frequently predicts the wrong outcome should not be used.

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[2] A complementary analysis of mean diameter would not be meaningful because neither the upper nor lower limit is well defined. Wider initial spacings tend to produce larger diameters up to the point where all trees are open-grown, but the plot data for this study do not include such low densities. For high-density stands at the opposite end of the scale, the mean diameter statistic is affected by the number of smaller Douglas-fir and shade-tolerant species in the understory.

CONCLUSION

The Density Management Diagram overestimates standing volume by 64% and mean diameter by 24%, on average. Volumes predicted for plantations established at initial densities between 300 and 3000 trees per hectare exceed nearly all the plots in the data base. Yield projections for widely spaced stands are particularly suspect.

The diagram, as formulated by Drew and Flewelling (1979), provides unattainable production targets and unrealistic silvicultural prescriptions, and strategic plans based on its predictions would likely be inaccurate. Consequently, the diagram cannot be used in its current form for silvicultural planning of Douglas-fir stands on the coast of British Columbia.

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